Bottom Interaction in Long Range Acoustic Propagation

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LONG-TERM GOALS

Observations and theory for ocean basin-scale acoustic propagation are based on nearly two decades of work in the North Pacific Ocean utilizing controlled sources and vertical and horizontal receiver arrays. Broadband sources are considered with typical center frequencies of 250, 75, and 28 Hz. Many aspects of observed long-range acoustic fields are statistical in nature because of scattering due to ocean internal waves and density compensated fine structure. There are two distinct scattering regimes observed in the broadband multipath arrival pattern (Figure 1)[*Colosi*, 2004]: one in which scattering is relatively weak and clear time-resolved wavefronts are evident, and one in which a complex interference pattern is seen. Associated with both regimes is significant in-filling of acoustic energy into deterministic shadow zones, especially when the receivers are near the seabed or when the sources are off the sound channel axis. The long-term goal of this project is to understand long-range acoustic propagation in the ocean, and at the moment we do no understand the physical mechanisms responsible for the leakage of coherent energy out of the sound channel.

OBJECTIVES

On previous NPAL (North Pacific Acoustic Laboratory) tests acoustic arrivals near 75Hz were observed on bottom-mounted hydrophones in the shadow zone well below the SOFAR channel. Dushaw et al [*Dushaw, et al.*, 1999] note "This result is surprising, and no currently available theory accounts for this anomalously deep acoustic energy." There are two prominent hypotheses to explain the energy in the shadow zones: 1) energy is scattered from internal waves and fine structure in the ocean, or 2) long range sound propagation in the ocean involves coupled modes between the ocean sound channel and the sub-seafloor [*Butler and Lomnitz*, 2002]. The latter hypothesis could involve scattering from roughness and lateral heterogeneity at the seafloor or shear wave and interface wave effects in the soft sediments.

There are two specific objectives of this project. 1) Quantitatively compare the signal (near 75 Hz) and noise levels on the hydrophones at the seafloor to the hydrophones in the sound channel. We believe that shadow zone arrivals are a ubiquitous feature of long range sound propagation in the ocean and we expect to see strong signals on the seafloor hydrophones. 2) By comparing the vertical particle velocity from the geophone to the pressure from the hydrophone we can infer the role of rigidity in the propagation process. For a plane wave in a uniform acoustic medium the ratio of pressure to velocity is simply the acoustic impedance (density times phase velocity) [*Jensen, et al.*, 1994]. For interface waves at the seafloor that are proposed to be a significant mechanism in the coupled mode problem,

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however, the relationship between pressure and particle velocity is more complicated and involves phase shifts depending on the type of interface waves [*Rauch*, 1980; *Sutton and Barstow*, 1990].

" A more specific science objective is to understand the acoustic energy that arrives near and below the critical depth (where the deep sound speed equals the highest sound speed in the upper ocean). In previous experimental work, both for NPAL and AMODE (*Dushaw et al*., 1999), we observed anomalously high signal to noise ratios at these great depths. Some of the observed effect may be due to decreased levels of ambient noise, but apparently not all. For this work the DVLA and the four ocean bottom seismometers (OBS) that we deployed around the DVLA are important assets. .... " (quoted from page 3 of the LOAPEX Cruise Report [*Mercer, et al.*, 2005])

APPROACH

The LOAPEX (Long-range Ocean Acoustic Propagation Experiment) vertical line arrays (VLA) are described on page 1 of the LOAPEX cruise report: " The hydrophone arrays on the two combined VLAs covered most of the 5-km water column. We refer to one of the VLAs as the deep VLA (DVLA), located at 33.418920°N latitude and 137.682470°W longitude. The DVLA combines a 40-element, 1400-m long array (2150–3550 m nominal) with a 20-element, 700-m long array (3570– 4270 m nominal) to span the lower caustics in the acoustic arrival pattern with a nominal spacing of 35 m. The DVLA was considered the primary receiving array for LOAPEX. The other moored array, the shallow VLA (SVLA), was moored 3 n mi due west of the DVLA. The SVLA has a 40-element, 1400-m long array (350–1750 m) centered approximately on the sound channel axis. Both hydrophone arrays are being tracked by a network of surveyed bottom transponders. "

Ocean bottom seismometer (OBS) instrumentation was "piggy-backed" on the NPAL/LOAPEX controlled source cruise that began in September 2004 [*Mercer, et al.*, 2005; *Mercer and Howe*, 2004]. The OBSs were recovered on the SPICE04 recovery cruise Direct funding for the OBS's came from WHOI and NSF. ONR provided the additional ship time for the deployments and recoveries. (We are particularly grateful to the Chief Scientists, Jim Mercer and Peter Worcester, for helping to make this possible.) The OBSs were retrieved on the SPICE04 recovery cruise in May 2005 [*Worcester*, 2005]. Our OBSs were each equipped with a hydrophone, so we have an important acoustic data point at the water-seafloor interface, and a vertical component geophone, to measure the seafloor response.

LOAPEX transmissions were made at seven stations at nominal ranges of 50, 250, 500, 1000, 1600, 2300 and 3200km from the VLAs. Water depths at the SVLA and DVLA are 5005 and 5045m respectively (the OBS's were deployed about 2km north south east and west from the DVLA in comparable water depths). Water depth along the 3200km path to the furthest transmission station varied between 4800 and 6000m with only three or four locations where the depth was shallower than 5000m (see Figure 2 of Mercer and Howe, 2004). From CTD casts at the seven stations the critical depth is everywhere shallower than 4600m. Since the water wavelength at 75Hz is about 20m the seafloor is many wavelengths below the critical depth and sound levels at the seafloor should be quite low based on conventional analysis.

Figure 1 [*Colosi*, 2004] compares the observed acoustic field from a long-range controlled source (top) to the predicted field assuming acoustic propagation in a laterally homogeneous oceanic waveguide (bottom). Note that in the observed field there is considerable energy in the shadow zones between wavefronts in the "early arriving region" and well-below the wavefronts in the "late arriving" or

"finale" region. This figure is only showing depths from about 900 to 1600m, well within the sound channel. Using the vertical arrays on NPAL/LOAPEX/SPICE04 figures like this can be generated for water depths from 350 to 4270m covering most of the sound channel. The hydrophones on the OBSs will provide data to quantify the energy at the seafloor (about 5000m) that leaks out of the sound channel, the time histories of this energy (as in Figure 1) and the acoustic signal to noise ratios on the seafloor. The coherence and phase shifts between the hydrophone and the vertical component geophone data can be used to infer the role of rigidity and interface waves in the bottom interaction process.

WORK COMPLETED

The geophone and hydrophone data from each of the four OBSs deployed on NPAL04 as well as the transfer functions of the instruments have been made available to the community from the Scripps OBSIP (Ocean Bottom Seismometer Instrument Pool) group. One of the four OBSs had a leak in a cable or connector and no useful acoustic or seismic data was obtained. The data from this OBS can however be used as a proxy for instrument noise. The VLA data and transfer functions are also available from a data server at Scripps.

There are three classes of work that can be carried out on this data. First, since the receivers are broadband, the data can be used to study ambient noise in the North Pacific and its relation to shipping, storms, marine mammals, etc. This could be particularly interesting when combined with other long time series data sets from the North Pacific such as at the Hawaii-2 Observatory. An understanding of the naturally occurring ambient noise and system generated ambient noise is important in interpreting the results of the experiment. Some preliminary work on ambient noise was done on this award to check the fidelity of the data.

Second all of the sensors were recording during the LOAPEX controlled source transmissions and the data, after time compression, can be used to quantify the propagation loss in, and leakage from, the ocean sound channel. This is the focus of this grant. The controlled source transmissions are summarized in the LOAPEX cruise report. We focused on the M-sequence transmissions. There were two center frequencies (68.2 and 75Hz), two source depths (350 and 800m), and eight ranges (50, 250, 500, 1000, 1600, 2300, 3200km along a single track as well as Kauai). Sixteen permutations of these parameters were deployed. For each of the sixteen we had geophone and hydrophone data on the three functioning OBSs and the VLAs. Between 300 and 1500 individual transmissions were shot for each permutation. As a summary of the results we stacked all of the time-compressed traces for each permutation. On the geophone channels, arrivals were observed on the stacked traces for all permutations except Kauai. On the OBS hydrophone channels, arrivals were only observed on the stacked traces for ranges of 1000km and less.

Third naturally occurring earthquake T-phase arrivals can be observed on the OBSs and VLAs. Analysis of these events will help to understand the physics of T-phase excitation and propagation. We are seeking funding for this from the NSF.

RESULTS

Power spectra have been used to confirm that the geophone and hydrophone channels are correctly labeled. After applying the appropriate transfer functions and sensitivities the hydrophone channel agrees with seafloor pressure data acquired at the Hawaii-2 Observatory site (Figure 2) which is in

comparable water depth to, and not far from, the NPAL site. Similarly the vertical acceleration data fall within the range of expected values based on land models (Figure 3).

The OBS with shorted inputs provides data that can be used as a proxy for system noise. Figure 2 shows that the NPAL hydrophone channel is noisier than H2O levels from about 3Hz to at least 30Hz. The similarity in slope between the functioning OBS's and the shorted OBS in this band suggests that the noise here is "system noise". Even though this spectra was computed for a time period when the M-sequence source was active at 50km range there is very little indication of the LOAPEX source in the hydrophone spectra. This contrasts with the geophone results in Figure 3 where the SNR for the LOAPEX signal is about 20dB. Since the spectra for the functioning OBSs and the shorted OBS overlay from about 8 to 200Hz (except for the LOAPEX source band) it appears that the geophone noise floor around the LOAPEX band is also system noise limited.

The stacks of the time compressed traces are remarkable (Figure 4). Even though the OBS hydrophone and geophone channels are on the seafloor about 20 wavelengths below the bottom of the sound channel, coherent arrivals can still be detected on the hydrophone out to 1000km and on the geophone out to 3200km. It is interesting that the relative levels for the hydrophone and geophone channels differ with time along the trace (see the top panel in Figure 4). Since we are in the shadow zone we cannot use an angle of incidence argument to explain this. The hydrophone and geophone must be sensitive in different ways to whatever scattering or mode effect is operating here.

By studying the coherence and the relative amplitude between the hydrophone and geophone channels we will be able to constrain the possible mechanisms for the noise (acoustic plane waves, Stoneley or Rayleigh interface waves, shear modes, etc). Also by studying the time dependence on the arrival time and amplitude of the events on the individual time-compressed traces we will be able to infer whether these are associated with transitory features in the water column or permanent features of the waveguide or on the seafloor. By studying the time history of the background ambient noise we will be able to identify time windows with predicted optimal SNR.

IMPACT/APPLICATIONS

Leakage has at least two consequences. First if energy leaks out of the waveguide in a systematic fashion, it will increase transmission loss for known modes in the waveguide. These will be scattering losses as opposed to intrinsic attenuation. If the leaked energy rumbles through the seafloor and re-emerges down range there will be less overall transmission loss, but in this case it could be interpreted as a new type of mode. Second leakage will result in detections and observations on non-traditional sensors such as deep boreholes in the seafloor in water depths well-below the critical depth. Our job is to observe and explain long-range sound propagation in the ocean and leakage is one thing that we cannot adequately explain.

TRANSITIONS

None

RELATED PROJECTS

None

REFERENCES

Butler, R., and C. Lomnitz (2002), Coupled seismoacoustic modes on the seafloor, *Geophysical Research Letters*, *29*, 57, 51-54.

Colosi, J. (2004), Theory of long-range acoustic propagation, paper presented at Seismo-acoustic applications in marine geology and geophysics workshop at Woods Hole, MA, University of Washington, Applied Physics Laboratory, July 2004.

Dushaw, B. D., et al. (1999), Multimegameter-Range Acoustic Data Obtained by Bottom-Mounted Hydrophone Arrays for Measurement of Ocean Temperature, *IEEE Journal of Oceanic Engineering*, *24*, 202-214.

Jensen, F. B., et al. (1994), *Computational ocean acoustics*, 1st ed., 612 pp., American Institute of Physics, New York.

Mercer, J., et al. (2005), Cruise Report: Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), 1-45 pp, Applied Physics Laboratory, University of Washington.

Mercer, J., and B. M. Howe (2004), Long-range Ocean Acoustic Propagation Experiment (LOAPEX) - Cruise Plan, 1-45.

Rauch, D. (1980), Seismic interface waves in coastal waters: A review, Report, SACLANT ASW Research Center, San Bartolomeo (SP), Italy.

Sutton, G. H., and N. Barstow (1990), Ocean-bottom ultralow-frequency (ULF) seismo-acoustic ambient noise: 0.002 to 0.4 Hz, *Journal of the Acoustical Society of America*, *87*, 2005-2012.

Worcester, P. (2005), North Pacific Acoustic Laboratory: SPICE04 Recovery Cruise Report, Recovery Cruise Report.

PUBLICATIONS

None

HONORS/AWARDS/PRIZES

Ralph Stephen, Woods Hole Oceanographic Institution, was elected Fellow of the Acoustical Society of America.

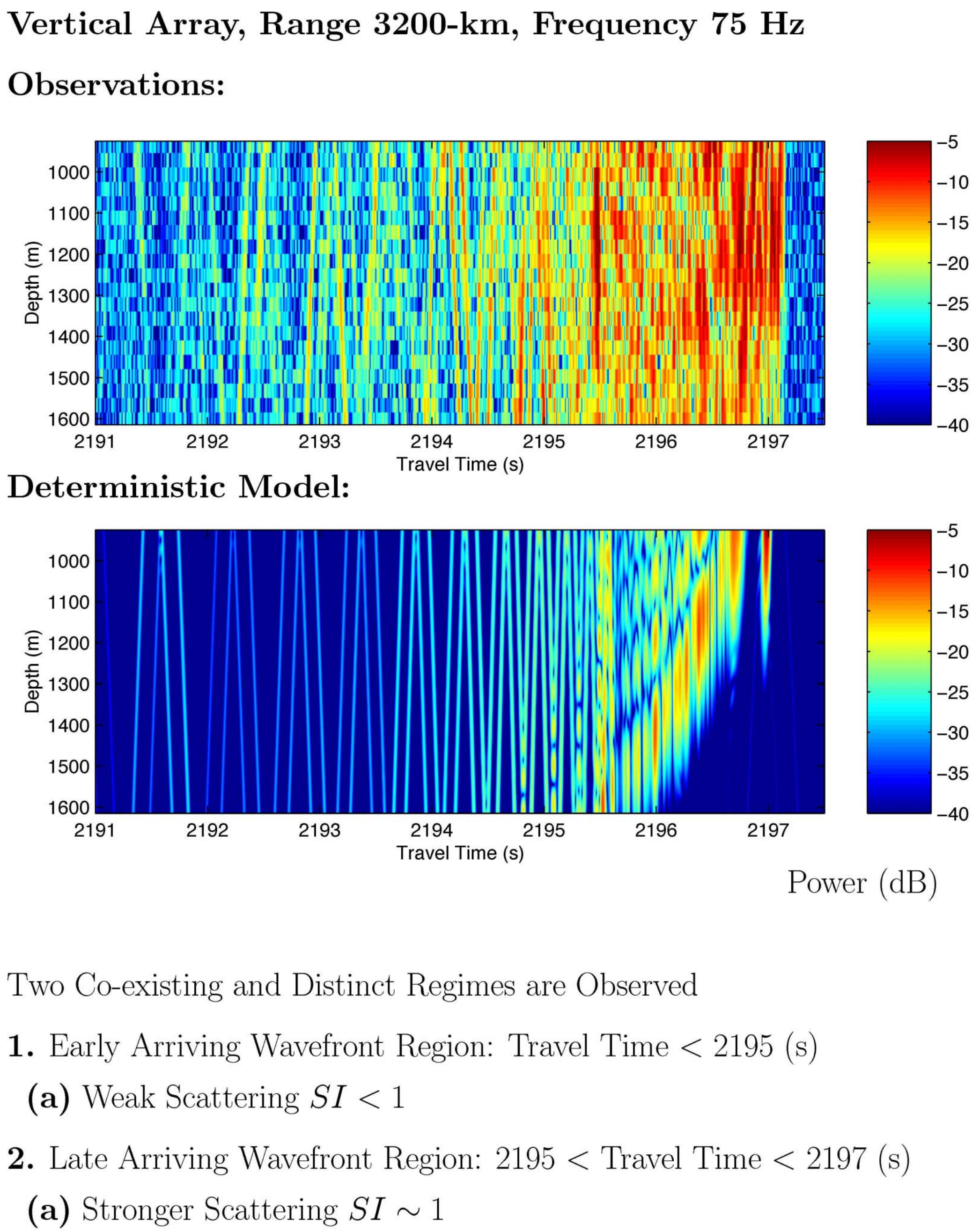

Figure 1: This figure [Colosi, 2004] compares the observed acoustic field from a long-range controlled source (top) to the predicted field assuming acoustic propagation in a laterally homogeneous oceanic waveguide (bottom). Note that in the observed field there is considerable energy in the shadow zones between wavefronts in the "early arriving region" and well-below the wavefronts in the "late arriving" or "finale" region. This figure is only showing depths from about 900 to 1600m, well within the sound channel.

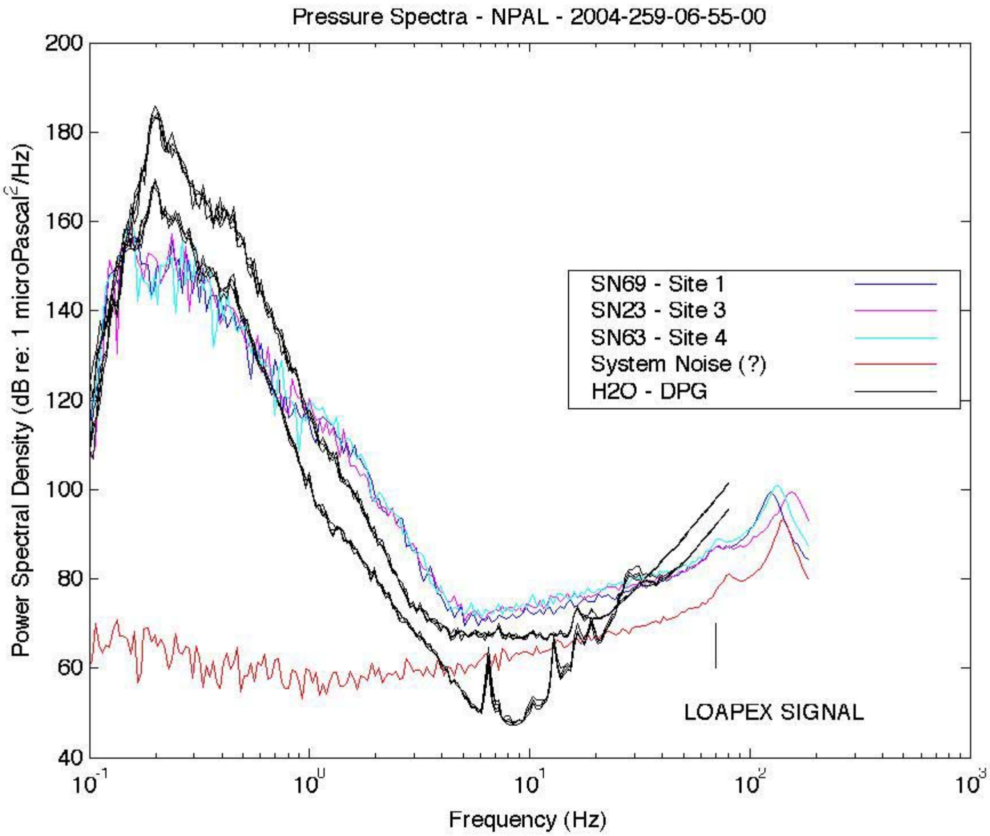

Figure 2: NPAL seafloor pressure spectra (red, cyan, magenta) have similar characteristics to other sites such as the Hawaii-2 Observatory (black). The red spectra corresponds to the OBS with shorted inputs which can be used as a proxy for system noise.

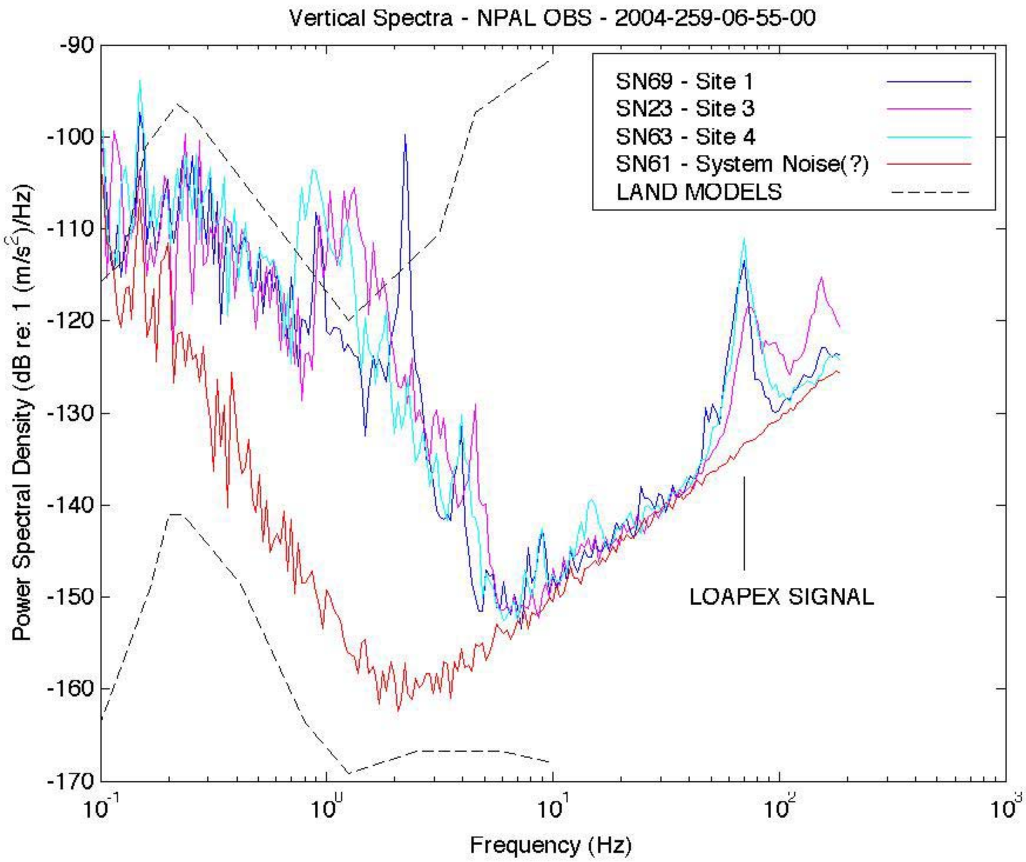

Figure 3: NPAL seafloor vertical acceleration spectra (blue, cyan, magenta) fall within the bounds of quiet and noisy sites on land (black-dash). The red spectra corresponds to the OBS with shorted inputs which can be used as a proxy for system noise. The LOAPEX signal appears quite clearly in this time window which corresponds to 75Hz M-sequence transmissions from 50km range.

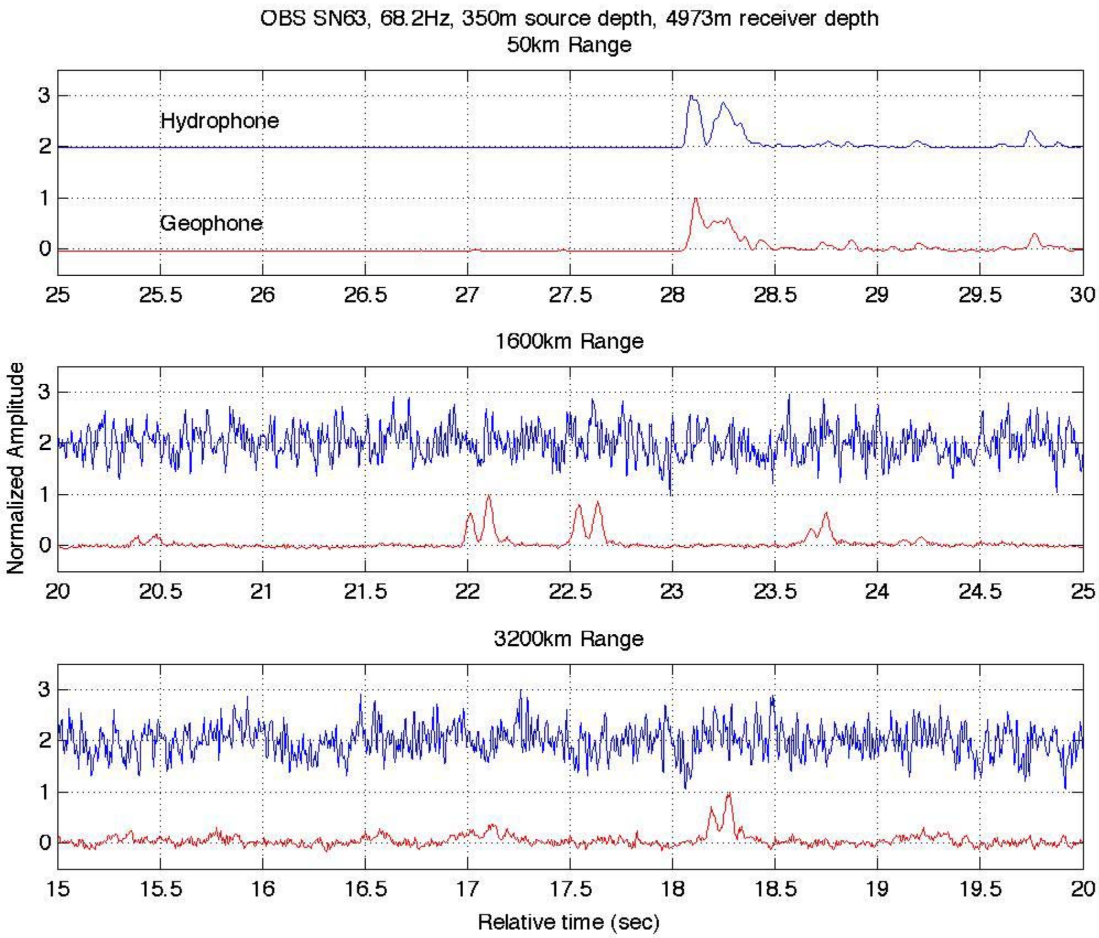

Figure 4: The time compressed geophone and hydrophone traces (stacked) for transmissions over three ranges: 50km, 1600km and 3200km. Both sensors are on the seafloor at a depth of about 5000m. Since the bottom of the sound channel is about 4600m, these sensors are deep (about 20 wavelengths) into the shadow zone. It is quite impressive that even over 3200m (the distance from Boston to Albuquerque) the geophone still detects coherent arrivals. All traces have been normalized to a maximum amplitude of 1 and they have been offset for easy viewing.